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Interaction of aerodynamic roughness length and windflow conditions and its parameterization over vegetation surface

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Surface aerodynamic roughness length is usually taken as a constant. In fact, it displays a remarkable dynamic change over underlying vegetation surfaces, because of the coupling of land surface roughness elements and windflow conditions. Current international research on this dynamic change and associated mechanisms is very limited. Using observations from different underlying surfaces (including forest, farmland and grassland) provided by a northern China coordinated observation test, the variation of aerodynamic roughness length, along with wind speed and friction velocity, is analyzed. We introduce two relationship fits, between aerodynamic roughness length and wind speed u, and dynamic variable u^2/u_*. Results show that aerodynamic roughness length has a clear dynamic change, and has complicated interactions with near-surface windflow. Further, the relationship fits between aerodynamic roughness length, u and u^2/u_*, are not only related to the roughness properties of the underlying vegetation surface (e.g. plant height), but also to plant dynamic response characteristics (e.g. flexibility). Aerodynamic roughness length decreases with increasing wind speed, because near-surface windflow conditions can change both plant roughness properties and airflow. However, the change of aerodynamic roughness length with friction velocity is complicated, and its sensitivities and transition points significantly depend on vegetation type. For underlying surfaces of forest and corn, with relatively substantial vegetative cover, roughness length correlates well with wind speed. For a surface with short vegetative cover, like natural lawn, the correlation is low. However, for all of the three vegetative surfaces, there is a close relation between roughness length and u^2/u_*, and their coefficients of fit from testing essentially represent the plant height and flexibility of different vegetation types. The test results also indicate that the parameterized relationships of roughness length over the underlying vegetation surface hold prospects for application.

underlying vegetation surface, windflow conditions, aerodynamic roughness length, interaction, parameterization

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Wind speed should approach zero at the land surface because of friction. Physically, however, the speed reaches this value at a certain height above the surface. This height is generally defined in earth science as the aerodynamic roughness length [1–3]. It is key to accurately calculating surface flux turbulence, and represents a major challenge to the development of atmospheric numerical model parameterization, and to improvements in weather analysis. Therefore, aerodynamic roughness length is one of the most important physical parameters at the earth surface.

It is difficult in practice to accurately calculate land surface aerodynamic roughness length [4]. It is usually determined using observed wind speed and air temperature profile data, or turbulent flux data from eddy covariance based on classical profile—flux relationships between roughness length and micro-meteorological elements [5–7]. The cal-

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culated roughness length is taken as a land surface process parameter in atmospheric numerical models [8,9]. Since most scientists consider aerodynamic roughness length as a geometric parameter that is determined by the structure and formation of surface roughness elements [10,11], it is often regarded as a constant. In past field experiments, scientists focused on the determination of fixed or seasonally variable roughness length parameters for certain typical underlying surfaces [12,13]. However, even with the same underlying surface, windflow will significantly change the structure and formation of flexible roughness elements, which affects the magnitude of aerodynamic roughness length [13]. Theoretically, aerodynamic roughness length is not a geometric parameter, but essentially a dynamic parameter [14]. It not only depends on the structure and formation of surface roughness elements, but also to some degree on near-surface windflow conditions [15], such as friction velocity, atmospheric stability, etc. Thus, all these factors cause substantial dynamic change in the aerodynamic roughness length for an underlying vegetative surface.

There is some current research on the relationship between aerodynamic roughness length and surface layer wind speed [13]. However, few works provide parametric models that objectively represent the dynamic change of aerodynamic roughness length, which is useful for atmospheric numerical models. Moreover, research on the interaction of surface layer windflow and aerodynamic roughness length is sparse, because of the entrenched understanding that the latter is only a geometric parameter [3,16]. The roughness length data obtained from international field tests cannot describe its dynamic change, but represent only its average. This is an especially difficult problem for vegetative surfaces with extremely flexible properties and special windflow conditions. Therefore, there are obvious limitations in the parameterization of aerodynamic roughness length for such surfaces in current numerical models. In the following, we systematically analyze the relationship between aerodynamic roughness length, windflow conditions, and physical properties of vegetation, using observed land surface process data collected by the northern China coordinated observation test [17,18]. In the process, we furnish some scientific references for the development of more reasonable parameterizations of aerodynamic roughness length for vegetated land surfaces.

1 Experiment and method

1.1 Experiment

The Northern China Observation Coordination and Integration Research in Semiarid and Arid Regions [17] (hereafter, the "northern China coordinated observation test") was organized by the Key Laboratory of Regional Climate-Environment Research for Temperate East Asia (RCE-TEA), the Chinese Academy of Sciences, and the Monsoon Asia Integrated Regional Study (MAIRS). The experiment involved 18 stations that mainly observed land surface processes. These stations operated simultaneously, under the same observation standards and instrument calibrations. Their data were subjected to the same quality controls, and are shared fully by all members [18,19].

The observations include weather elements, such as surface air pressure and precipitation, plus micro-meteorological elements such as wind speed, temperature and humidity profiles, land surface radiation and energy balance, soil temperature and humidity profiles. References [17–19] detail the performance and technical specifications of observational instruments. The data we used were collected during July and September 2008; they are relatively reliable, since there was no obvious seasonal variation in vegetation height. The data represent underlying surfaces of forest, farmland and grassland. These three can represent the main vegetation surface types. Consequently, the observations can be used to study the influence of different vegetation types on the relationship between aerodynamic roughness length and windflow. To test and verify the reliability of our results, we selected an additional two stations, representing farmland and grassland.

1.2 Field sites

The representative site for forest is Dayekou alpine forest station, which is on the north slope of Qilian Mountain, 38.53°N, 100.25°E, altitude 2835 m. This area has a typical alpine semiarid climate, with annual average rainfall 410 mm and temperature 6.36°C. The surface is covered by spruce trees, mainly 15–20 m in height. The terrain is open and even, within an area of 25 hm^2. An ultrasonic anemometer is at a height of 20.25 m. The farmland representative site is Tongyu farmland station, in Tongyu County, Baicheng, Jilin Province, at 44.88°N, 122.88°E, altitude 184 m. This area has continental semi-arid climate, with annual rainfall 400 mm and annual temperature 22.0°C. The surface is semiarid farmland, mainly covered by corn (about 1.8 m high). The soil is mainly composed of sandy soil and chernozem. The terrain is even and open, within an area over 50 hm^2. The ultrasonic anemometer is at 2 m height. The grassland representative site is Tongyu grassland station, with geographic location and climate very similar to Tongyu farmland station. The surface is covered by herbaceous, wild plants (about 10 cm in height), such as achnatherum sibiricum, reed, ephedra sinica, and liquorice; coverage is about 60%. The terrain is open and even, within an area of 1000 hm^2. The ultrasonic anemometer is at 3.5 m height. Figure 1 shows pictures of the field surrounding each site. The two sites selected for verification are Linze farmland station in Gansu Province, and Dongsu grassland station in Inner Mongolia. Linze is at 39.35°N, 100.13°E, at altitude 1384 m. It is in a temperate desert climate, with annual rainfall 120 mm and temperature 19.2°C. The surface is

Figure 1 The observation fields of Dayekou forest site (a), Tongyu farmland site (b), and Tongyu grassland site (c).

covered by crops (corn, wheat, etc.) that depend primarily on inland river irrigation. The terrain is open and even, within an area of 50 hm^2. The ultrasonic anemometer is at 4 m height. Dongsu is at 44.09°N, 113.57°E, at altitude 970 m. It is in a temperate semiarid and arid continental climate, with annual rainfall 185 mm and average temperature 23.3°C. The surface is desert steppe, and dominant species include speargrass and allium polyrrhizum. The terrain is open and even, within an area of more than 1000 hm^2. The ultrasonic anemometer is at 2.15 m above ground.

1.3 Method

According to Monin-Obukhov similarity theory [20], the profile of mean wind speed u in the atmospheric boundary layer can be written as

$$u(z)=\frac{u_*}{k}\left[\ln\left(\frac{z-d}{z_0}\right)-\psi_m\left(\frac{z-d}{L}\right)\right], \tag{1}$$

where z_0 is aerodynamic roughness length (m), d is zero plane displacement height (m), z is the observational height above the surface (m), $u(z)$ is the wind speed at the height of z (m/s), u_* is friction velocity (m/s), L is the Monin-Obukhov length (m), and ψ_m is the dimensionless stability correction function. Wind speed $u(z)$ is directly measured, and d can be estimated by vegetation characteristics. The Monin-Obukhov length L is calculated from micro-meteorological observation [21]. ψ_m is determined as follows.

When $z/L<0$,

$$\psi_m\left(\frac{z-d}{L}\right)=\ln\left[\frac{1+x^2}{2}\right]+2\ln\left(\frac{1-x}{2}\right)-\tan^{-1}(x)+\frac{\pi}{2}, \tag{2}$$

$$x=\left(1-16\left(\frac{z-d}{L}\right)\right)^{\frac{1}{4}}, \tag{3}$$

when $z/L>0$,

$$\psi_m\left(\frac{z-d}{L}\right)=-5\frac{z-d}{L}, \tag{4}$$

when $z/L=0$,

$$\psi_m\left(\frac{z-d}{L}\right)=0\,. \tag{5}$$

Consequently, from eq. (1), the aerodynamic roughness length can be derived as

$$z_0=(z-d)\mathrm{e}^{-\left(\kappa\frac{u}{u_*}+\psi_m\left(\frac{z-d}{L}\right)\right)}. \tag{6}$$

2 Dynamic change of aerodynamic roughness length and its interaction with windflow

Among the complex factors affecting aerodynamic roughness length (z_0), the key theoretical one is undoubtedly the surface roughness element [10,11]. The roughness length of an underlying vegetation surface can vary remarkably with plant heights and densities of different vegetation types. As shown in Figure 2(a), the average roughness lengths of forest, farmland, and grassland are 0.5826, 0.2341 and 0.0641 m, respectively. These values are consistent with the recent work of Stull, who obtained corresponding values of 0.53, 0.25 and 0.03 m [22]. This indicates that our measured roughness lengths are reliable.

Figure 2(a) also shows that high vegetation has larger average z_0, and the differences between the three vegetation surfaces are significant, reaching an order of magnitude. This indicates that vegetation height, as the most fundamental characteristic of roughness elements on a vegetative surface, crucially affects z_0 and determines its order of magnitude.

Figure 2(b) demonstrates that the ratio of standard deviation of z_0 to its average is relatively high for every surface type, 0.30, 0.24 and 0.23 for forest, farmland and grassland, respectively. Although some variability is unavoidable because of errors arising from the determination of z_0, the ratios are beyond the general scope [21]. Nevertheless, it is clear that the z_0 of vegetation surfaces is not a constant but a dynamic variable, and its variation is most likely attributable to flexible properties of vegetation roughness elements, which are in turn sensitive to wind speed.

Figure 3 shows the variation of z_0 over different wind speed intervals, for forest, farmland and grassland surfaces.

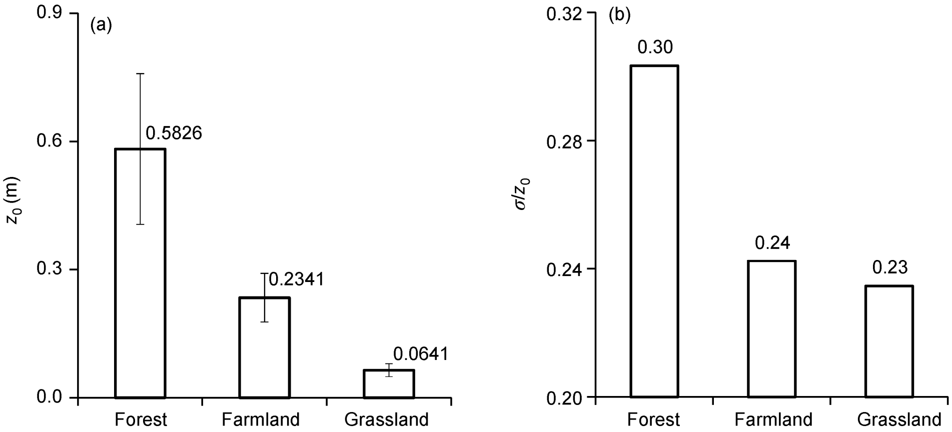

Figure 2 Comparison of mean aerodynamic roughness lengths z_0 and their standard deviations (a); and the ratio of standard deviation σ to z_0 (b), for forest, farmland, and grassland underlying surfaces.

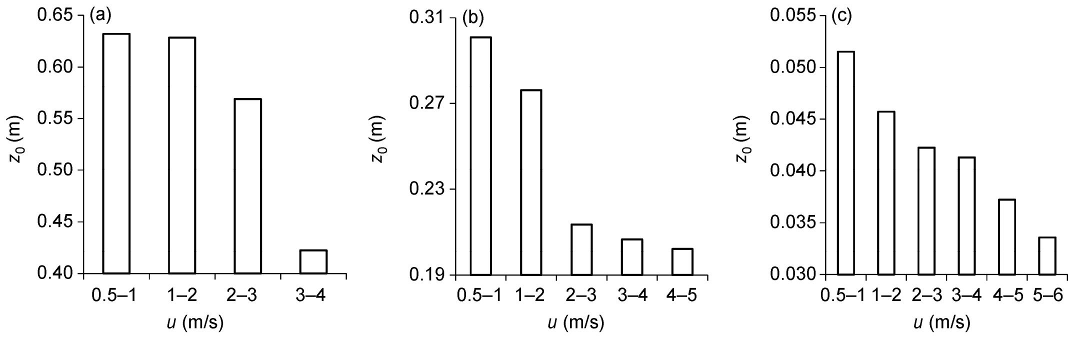

Figure 3 Distributions of roughness length at various wind speed intervals over forest (a), farmland (b), and grassland (c) underlying surfaces.

The figure shows that z_0 is greater under weak winds and smaller under strong ones, for all surfaces. In forests, z_0 is not sensitive to wind speed variation until it increases to 3–4 m/s. This indicates that stronger winds are necessary to change the height and structure formation of thick trunk vegetation, as in forests. The z_0 of farmland changes dramatically once wind speeds reach 2–3 m/s, although it becomes less sensitive at stronger speeds. This is because corn plants are more slender and denser than trees. For grassland, z_0 is sensitive to wind speed variability at all speed intervals, which is consistent with the slim, low properties of herbaceous vegetation.

Apart from speed, windflow also influences the magnitude of z_0 for vegetation surfaces [15,16]. This is because the height at which wind speed drops to zero is controlled by surface downward momentum transmission processes, that is, by the ability of surface roughness elements to absorb momentum [23]. This ability is correlated with air pressure, which is affected by interaction between near-surface windflow and surface roughness elements. This interaction can be described by the dynamic characteristic of friction velocity. For vegetated surfaces, the effect of windflow on roughness is primarily related to the interaction of friction velocity and plant groups. In the early 1950s, Charnock considered the relationship between z_0 and friction velocity [24], and there have been follow-up studies [25]. However, these works mainly address the relationship over the ocean, and little attention has been paid to vegetated land surfaces.

Figure 4 shows the distribution of z_0 across different friction velocity intervals, over forest, farmland and grassland surfaces. This indicates that roughness length has an even more complicated relationship with friction velocity than with wind speed. Over each underlying surface, roughness length decreases with friction velocity when the latter is small, but increases with it at friction velocities greater than 0.5–0.6 m/s.

The complex relationship between z_0 and friction velocity is attributed to a dual role of friction velocity. On one hand, this velocity is a primary dynamic characteristic quantity of surface windflow. On the other hand, it partly originates from wind speed. As exhibited in Figure 5, there is significant correlation between friction velocity and wind speed. Consequently, at low friction velocities, these velocities primarily reflect the impact of wind speed on z_0. At high friction velocities, they largely reflect the influence of the aerodynamic property of friction velocity on z_0.

The roughness elements of vegetation surfaces portrayed in Figure 6 have some similarity to water, but are different from rigid roughness elements, such as buildings or bare

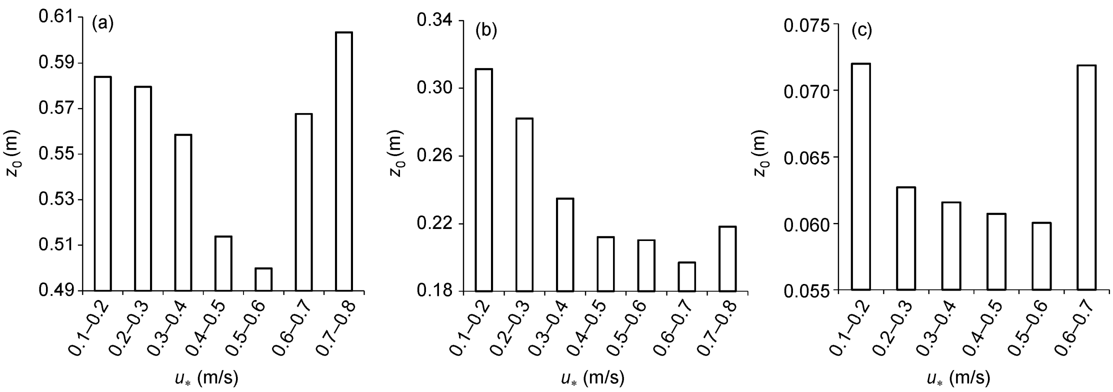

Figure 4 Distributions of z_0 across various friction velocity intervals, for forest (a), farmland (b), and grassland (c) underlying surfaces.

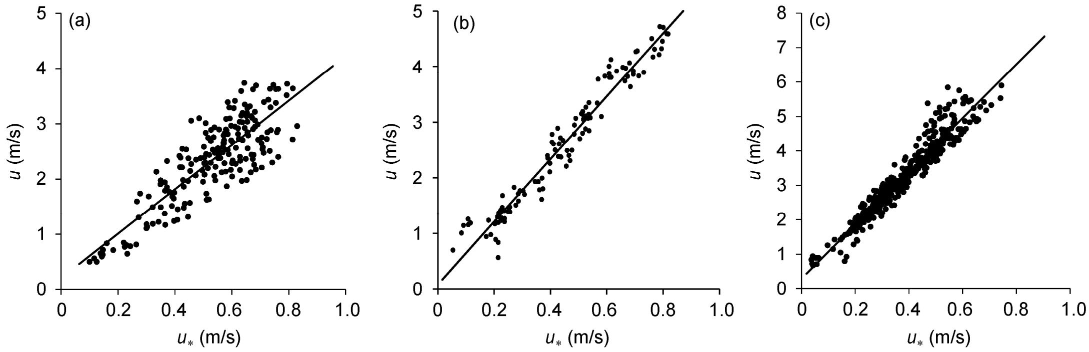

Figure 5 Relationships between wind speed u and friction velocity u_*, for forest (a), farmland (b), and grassland (c) underlying surfaces.

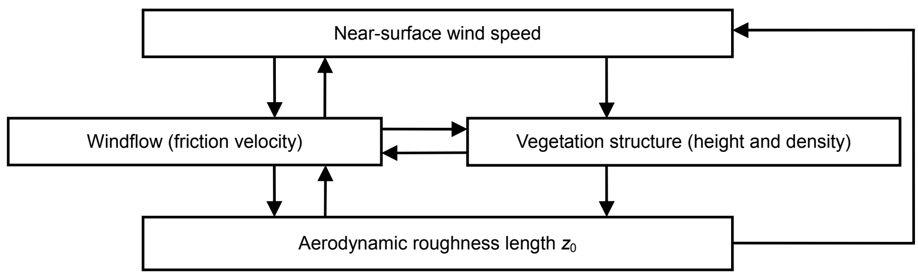

Figure 6 Schematic diagram of couplings between z_0 and windflow.

surfaces, like desert and ice [26]. Their structure and formation are significantly modified by windflow conditions. Further, the coupling between z_0 and windflow is substantial, because of the direct effects of windflow on z_0.

3 Parameterized relations between aerodynamic roughness length and windflow, and their verification

To parameterize the dynamic change of z_0 over vegetated surfaces, it is necessary to systematically explore relationships between z_0 and aerodynamic variables, like wind speed and friction velocity. Figure 7 displays a scatter plot and curve fit of the relationship between z_0 and wind speed over forest, farmland, and grassland surfaces. This reveals that z_0 values for the three surfaces decrease with wind speed. The values for forest and farmland surfaces show significant correlation with wind speed, with correlation coefficients 0.48 and 0.62, respectively. The correlation is weak for grassland, with a correlation coefficient of 0.22. This suggests that the roughness properties of higher vegetation are significantly modulated by wind speed, but not so for low vegetation.

The mathematical expression of the theoretical relationship between z_0 and wind speed may be expressed based on the form of eq. (6) as

$$z_0 = a\mathrm{e}^{-bu}, \tag{7}$$

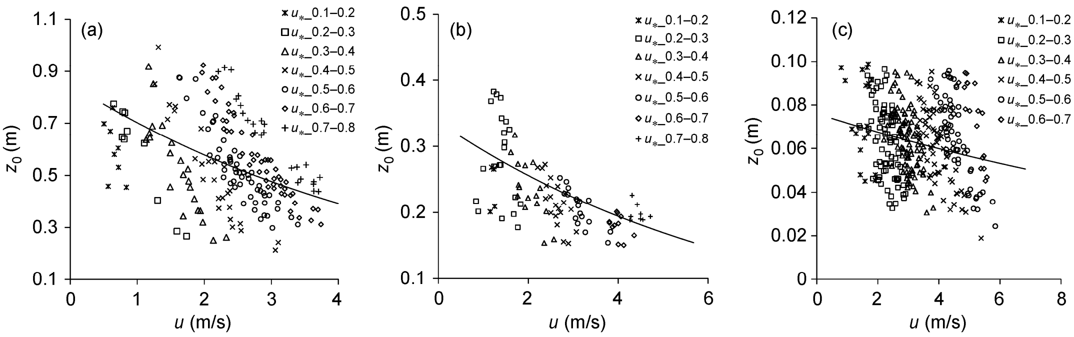

Figure 7 Scatter plots and curve fits for relationships between z_0 and wind speed u over forest (a), farmland (b), and grassland (c) underlying surfaces.

where z_0 and u have already been defined, and a and b are test parameters. In the functional form of eq. (7), a and b are not simply empirical parameters, but have clear physical interpretation. Parameter a is actually z_0 at static wind, and is related only to vegetation height and density [11]. In theory, the higher the vegetation is, the larger is parameter a. Parameter b reflects the sensitivity of vegetation to aerodynamics, and is the dynamic response coefficient of vegetation. It is related to vegetation height and flexibility, especially the former.

Figure 7 shows curve fits from eq. (7), using data for the forest, cropland and grassland surfaces. Table 1 lists the statistics of fit for each surface. The results show that there are marked differences in the value of parameter a, i.e. the calm wind roughness length. These values are 0.773 m, 0.313 m and 0.076 m over forest, cropland and grassland surfaces, respectively. They are similar to those of z_0 presented in Figure 2, but absolute values are much larger. This is another indication of the strong influence of near-surface wind speed on z_0. Parameter b, the dynamic response coefficient, also varies with vegetation surface, decreasing from forest to farmland to grassland. This signifies the decline in the influence of wind speed, from forest to farmland to grassland. These findings reveal that vegetation height can modulate the degree of aerodynamic effect on vegetation roughness properties.

In Figure 7, z_0 is plotted against wind speed over different friction velocity intervals, marked with different symbols. The data points are rather discrete for each surface. The discreteness is mainly attributed to the dynamic change of friction velocity, and thus the discreteness decreases markedly within the same friction velocity interval.

Figure 8 shows the relationship between z_0 and friction velocity for the three surfaces. Correlations are clearly lower than the relationship between z_0 and wind speed. The corrections are also more complicated, especially for grassland. This is consistent with the earlier conclusion that friction velocity plays a dual role, i.e. variable with wind speed, but also an important dynamic characteristic quantity. Nevertheless, the two roles conflict, and the dominant one is fully determined by the interaction between windflow and vegetation structure and formation. For higher vegetation like forest and farmland, friction velocity is primarily related to wind speed when it has low values, but acts as a windflow characteristic quantity at high values.

Table 1 Statistics of fit between roughness length and wind speed u

Underlying surface	a (m)	b	Correlation coefficient	Standard deviation (m)
Forest	0.773	0.19	0.48	0.02611
Farmland	0.313	0.14	0.62	0.00261
Grassland	0.076	0.06	0.22	0.00027

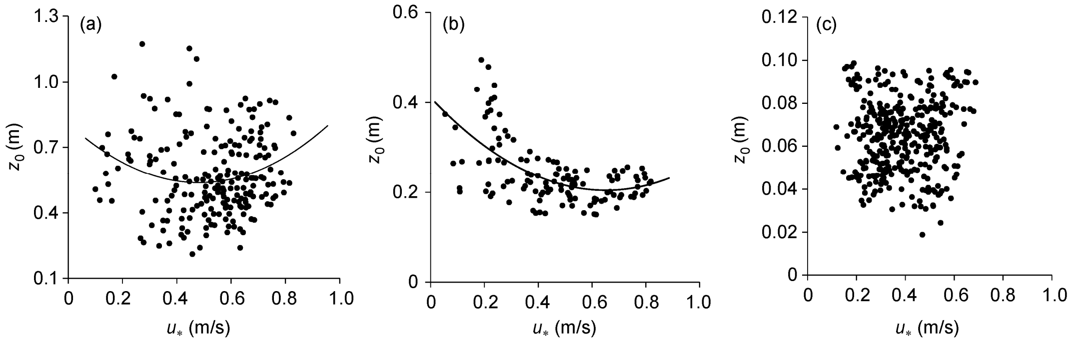

Figure 8 Scatter plots and fits of the relationship between z_0 and friction velocity u_* over forest (a), farmland (b), and grassland (c) underlying surfaces.

The above analysis demonstrates that z_0 of a vegetated surface has weak correlation with friction velocity, and its relation with wind speed also has certain discreteness. However, in terms of its basic properties, z_0 decreases with wind speed at a constant friction velocity, and it increases with friction velocity at a constant wind speed. Its change is more sensitive to wind speed than to friction velocity. To consider both variables together, we establish a comprehensive dynamic quantity u^2/u_* that efficiently describes the relationship between roughness length and near-surface windflow.

A scatter plot of the relationship between roughness length and u^2/u_* for forest, farmland and grassland underlying surfaces is presented in Figure 9. Results suggest that the z_0 of a vegetated surface correlates better with the quantity u^2/u_* than with the single factors of friction velocity u_* or wind speed u. Roughness length declines significantly with increasing u^2/u_*. The correlation coefficients are 0.74, 0.69 and 0.47 for forest, farmland and grassland surfaces, respectively. Standard deviations are also significantly improved, even for the grassland surface. Similarly, another relationship fit can be established as

$$z_0 = c\mathrm{e}^{d\frac{u^2}{u_*}}. \tag{8}$$

In eq. (8), c and d are test parameters like a and b, and they are related to the structure and formation of vegetation. The fit statistics of roughness length and u^2/u_* listed in Table 2 show that parameter c is close to parameter a from Table 1, because of their consistent physical interpretation. Technically speaking, c and a should be identical because they both represent z_0 under calm wind, but they are not exactly equal because of errors in the fit. Parameters d and b are different in physical interpretation, but they both represent the response of vegetation to windflow, and thus they decrease with decreasing plant height.

To verify the reliability of the parameterized fit relations, we compare the measured z_0 of other sites with ones estimated by eqs. (7) and (8). Since no other forest site is available, we select Tongyu grassland and Linze farmland stations to evaluate the simulation capabilities of those equations. Figure 10 compares the measured z_0 with ones estimated by the equations. This shows that both fits are practical, but the capability of eq. (8) is superior. Table 3 shows that the correlation coefficients for measured and estimated z_0 are 0.51 and 0.62, respectively. Their standard deviations are 0.138 m and 0.109 m, and deviations 0.042 m and 0.037 m, respectively. Eqs. (7) and (8) not only quantitatively describe the dynamic change of z_0 in land surface models, but also aid the attainment of regional or grid-scale

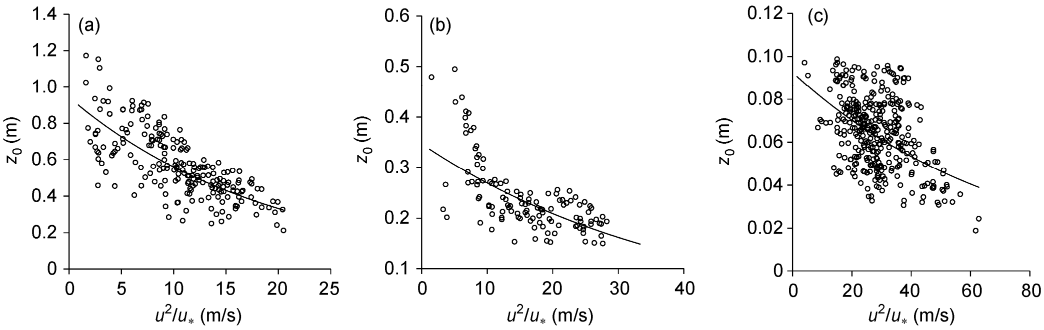

Figure 9 Scatter plots and curve fits of the relationship between aerodynamic roughness length z_0 and u^2/u_* over forest (a), farmland (b), and grassland (c) underlying surfaces.

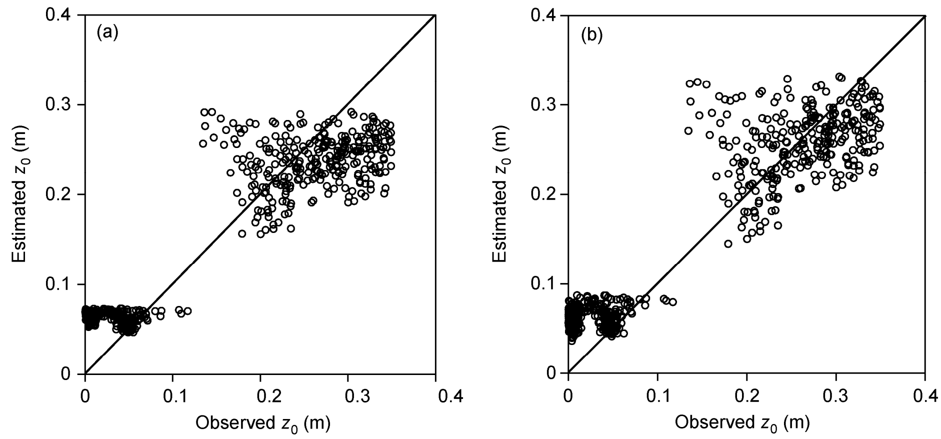

Figure 10 Comparison between estimated and observed z_0, by fitting eqs. (7) (a) and (8) (b).

Table 2 Statistics of fit between roughness length and u^2/u_*

Underlying surface	c (m)	d	Correlation coefficient	Standard deviation (m)
Forest	0.943	0.052	0.74	0.01612
Farmland	0.347	0.025	0.69	0.00211
Grassland	0.092	0.012	0.47	0.00023

Table 3 Test statistics of z_0 fit relations

Parameterized relation	Correlation coefficient	Standard deviation (m)	Deviation (m)
$z_0 = ae^{-bu}$	0.51	0.138	0.042
$z_0 = ce^{d\frac{u^2}{u_*}}$	0.62	0.109	0.037

z_0 when the distribution of vegetation types is known [27,28].

4 Discussions and conclusions

In contrast with rigid roughness elements like buildings, or bare surfaces like desert and ice, the aerodynamic roughness length z_0 of underlying vegetation surfaces is no longer treated as a constant. Instead, it is treated as a dynamic quantity that depends on the flexibility of surface roughness elements. Near-surface windflow significantly changes z_0 by altering vegetation structure and formation, as well as windflow conditions. The higher the vegetation is, the greater its effect on z_0, and the greater the dynamic change of z_0.

The roughness length varies with near-surface wind speed and friction velocity. It is larger for low wind speed and smaller for high wind speed. The case is more complicated for friction velocity; z_0 is small for a moderate friction velocity, but greater for small or large friction velocities. Moreover, z_0 of different vegetation types has varying sensitivity to near-surface wind speed and friction velocity. It does not significantly decrease until wind speed exceeds 3–4 m/s over a forest surface. Wind speeds of 2–3 m/s or more significantly change z_0 over farmland, and z_0 over grassland is sensitive across the entire wind speed range. These variations are closely related to the height and flexibility of different types of vegetation.

Roughness length is complexly coupled to windflow conditions over a vegetated surface, which not only affects properties of vegetation roughness elements, but also closely correlates to near-surface windflow. Correlation coefficients between z_0 and wind speed are 0.48, 0.62 and 0.22 over forest, farmland and grassland surfaces, respectively, the latter value indicating a weak correlation. Correlation coefficients between z_0 and u^2/u_* reach 0.74, 0.69 and 0.47, along with more satisfactory standard deviations. This is further testament to the impact of windflow on z_0. The test parameters from the parameterized fit relations between z_0, wind speed u and u^2/u_* are primarily controlled by average vegetation height.

Fit equations (7) and (8) have a clear physical interpretation and are effectively evaluated using observational data. Eq. (8) is more theoretically reasonable, and its test results are superior. The two fits provide an important scientific reference for quantitative description of vegetation z_0 for land surface models.

This paper reveals something about the physical relations between z_0 of vegetated surfaces and near-surface windflow. However, understanding of the sensitivities and transition points in the relationships between z_0, wind speed and friction velocity are hindered by inevitable z_0 calculation errors. In addition, the accuracy of our results is limited by minus changes of vegetation height during the observation period. Therefore, there is a need for more systematic scientific field experiments and wind tunnel experiments, to expand on these results.

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